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Origin and Ubiquity of Short-Period Earth-like Planets: Evidence for the Sequential-Accretion Theory of Planet Formation

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ABSTRACT

The formation of gas giant planets is assumed to be preceded by the emergence of solid cores in the conventional sequential-accretion paradigm. This hypothesis implies that the presence of earth-like planets can be inferred from the detection of gas giants. A similar prediction cannot be made with the gravitational instability (hereafter GI) model which assumes that gas giants (hereafter giants) formed from the collapse of gas fragments analogous to their host stars. We propose an observational test for the determination of the dominant planet-formation channel. Based on the sequential-accretion (hereafter SA) model, we identify several potential avenues which may lead to the prolific formation of a population of close-in earth-mass ($M_\oplus$) planets (hereafter close-in earths) around stars with 1) short-period or 2) solitary eccentric giants and 3) systems which contain intermediate-period resonant giants. In contrast, these close-in earths are not expected to form in systems where giants originated rapidly through GI. As a specific example, we suggest that the SA processes led to the formation of

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the 7.5 $M_\oplus$ planet around GJ 876 and predict that it may have an atmosphere and envelope rich in O_2 and liquid water. Assessments of the ubiquity of these planets will lead to 1) the detection of the first habitable terrestrial planets, 2) the verification of the dominant mode of planet formation, 3) an estimate of the fraction of earth-harboring stars, and 4) modification of bio-marker signatures.

Subject headings: planetary systems: formation – planetary systems: protoplanetary disks – planets and satellites: formation – solar system: formation – stars: individual (GJ876)

1. Introduction

The search for habitable planets is essential in the quests to unravel the origin of the Solar System and find life elsewhere. Extra solar planets with mass (M_p) down to that of Neptune (Marcy et al. 2005; Santos et al. 2004) are thought to be gas giants because some have densities comparable to that of Jupiter. Extrapolation on the fraction of stars which host the yet-to-be-detected $M_\oplus$ terrestrial planets depends on the assumed models of planet formation. If giants were formed through gas accretion onto pre-assembled cores (Pollack et al 1996), they would be accompanied by many earth-like planetary siblings. However, in systems where giants were formed through GI (Boss 1997), such an association would be coincidental.

Both models were introduced and modified to account for the observed properties of giants and extra solar planets. Several solutions (Hubickyj et al. 2004; Alibert et al. 2005) have been suggested to bypass the protoplanetary growth bottlenecks associated with the early SA models. Likewise, photoevaporation has been adopted into the GI model (Boss 2003) to address the giants' internal structure and correlation with metal-rich stars. While these revisions have led to a more comprehensive understanding of the planet-formation process, they have also reduced the capability to falsify the models.

We present a robust observational test to differentiate the SA and GI models. In §2, we briefly recapitulate their essential features. Based on the SA model, we identify in §3 several potential avenues which may lead to the prolific formation of a population of close-in earths around stars with 1) short-period, 2) solitary eccentric gas giants, or 3) intermediate-period resonant planets. As a specific example, we suggest in §4 that the dynamical structure of the system (two giants with 30 and 60 day orbits plus a 7.5 $M_\oplus$ planet with a 2-day orbit) around GJ 876 (with a mass $M_* = 0.32 M_\odot$) was established when the migrating resonant giants induced dynamical evolution of residual embryos and led to the formation of the close-in

earth. Since the embryos of this planet formed outside the snow line, it is mainly made of water and it probably has an oxygen-rich atmosphere. In §5, we summarize the dominant SA processes which promote the formation of close-in earths. Since these planets are not expected to form if the giants originated through GI (Boss 1997), they provide an observable test for the SA and GI models.

2. Differences between SA and GI models

In the SA paradigm, planetesimals coagulate via runaway growth and become protoplanetary embryos (with mass M_e) by oligarchic growth (Kokubo & Ida 1998) on a time scale $\tau_{\rm growth}$. In gaseous disks, the embryos' growth are stalled (Lissauer 1987) when they have swept clean the planetesimals within their feeding-zone of full width $\Delta_{\rm fz} \sim 10-12R_h$, where $R_h = (M_e/3M_*)^{1/3}a$ and a are their Hill's radius and semi major axis. For a fiducial surface density $\Sigma_{d,g} = \Sigma_{od,og} f_{d,g}(a/1{\rm AU})^{-3/2}$ [the subscripts d, g refer to the heavy elements and gas with scaling factors f_d and f_g with respect to the minimum mass nebular model (hereafter MMN) for the mass distribution inside 1 and 10 AU around the Sun (Hayashi et al. 1985)], the isolation mass is

$$M_{\rm iso} = 0.12 f_d^{3/2} \gamma_{\rm ice}^{3/2} (\frac{\Delta_{\rm fz}}{10R_h})^{3/2} (\frac{a}{\rm AU})^{3/4} (\frac{M_*}{M_\odot})^{-1/2} M_\oplus. \quad (1)$$

The normalizations, $\Sigma_{od} = 10\gamma_{\rm ice}{\rm g~cm}^{-2}$ and $\Sigma_{og} = 2.4 \times 10^3 f_{\rm dep}{\rm g~cm}^{-2}$ are determined by the volatile-ice enhancement [interior ($\gamma_{\rm ice} = 1$) and exterior ($\gamma_{\rm ice} = 4$) to the snow line (Ida & Lin 2004; Ida & Lin 2005) at $a_{\rm ice} \simeq 2.7(M_*/M_\odot)^2$ AU] and the gas-depletion factors at time τ_* since the onset of star formation [$f_{\rm dep} = \exp(-\tau_*/\tau_{\rm dep})$ where the gas depletion time scale $\tau_{\rm dep}$ is observed (Hartmann 1998) to be a few Myr].

Prior to severe gas depletion, the embryos' eccentricities (e_e's) are damped (Ward 1993) on a time scale $\tau_{\rm e,damp} \simeq 300 f_g^{-1} f_{\rm dep}^{-1} (M_e/M_\oplus)^{-1}(a/1{\rm AU})^2$ yr $<< \tau_{\rm growth}$. Isolated embryos emerge on a time scale $\tau_{\rm iso} = 3\tau_{\rm growth}$, where

$$\tau_{\rm growth} \simeq 0.12 \gamma_{\rm ice}^{-1} f_d^{-1} f_g^{-2/5} \left(\frac{a}{1{\rm AU}}\right)^{27/10} \left(\frac{M_{\rm iso}}{M_\oplus}\right)^{1/3} \left(\frac{M_*}{M_\odot}\right)^{-1/6} {\rm Myr}. \quad (2)$$

In disks with $\tau_{\rm growth} < \tau_{\rm dep}$, the embryos' growth at $a < a_{\rm ice}$ is limited by $M_{\rm iso} << M_\oplus$. Just outside $a_{\rm ice}$, f_d is enhanced by the grains' interaction with the disk gas (Stevenson & Lunine 1988), with $M_e > M_{\rm core}(\sim 3-10M_\oplus)$ required for efficient gas accretion (Hubickyj et al. 2004) so that primary giants emerge there. However, in low-Σ_d disks, no giants can form because $\tau_{\rm growth}(M_{\rm core}) > \tau_{\rm dep}$ even with a local f_d enhancement. In modest-Σ_d disks, when

$\tau_{\rm growth}(M_{\rm core}) \sim \tau_{\rm dep}$, the rate of gas accretion and the asymptotic M_p are limited by the global disk depletion or local gap formation (Bryden et al. 1999). Beyond the gap, grains and planetesimals accumulate which promote the emergence of secondary giants with a delay of $\Delta\tau$ (Bryden et al. 2000).

During the active disk-evolution phase, giants also migrate (Ida & Lin 2004) on a time scale

$$\tau_{mig} \simeq 0.8 f_g^{-1} f_{\rm dep}^{-1} (M_p/M_J)(M_\odot/M_*)(10^{-4}/\alpha)(a/1{\rm AU})^{1/2}{\rm Myr}, \tag{3}$$

where α is an *ad hoc* scaling parameter for angular momentum transfer efficiency. In persistent disks, extensive migration leads to short-period planets (Lin et al. 1996), but in rapidly depleting disks, they may be stalled. Multiple planets formed in slowly evolving disks (with $\Delta\tau > \tau_{mig}$) attain wide separations (*eg* Ups And). In rapidly evolving disks (with $\Delta\tau < \tau_{\rm dep}$ and $< \tau_{\rm mig}$) the migration of successive emerging planets lead to resonant capture (Lee & Peale 2002) (*eg* GJ 876 and 55 Can). As they continue to migrate, the giants' eccentricities (e_p's) are excited by their resonances and damped by their tidal interaction with the gas beyond the gap (Kley et al. 2004) on a time scale $\tau_{\rm p,damp} \sim \tau_{mig}$.

In the SA hypothesis, giants form outside the snow line while many embryos with $M_{\rm iso}$ remain in the inner disk. In the GI model, giants must form in massive disks which can efficiently cool (Gammie 2001; Durisen et al. 2005). These conditions are only satisfied in the optically-thin outer regions of disks around stars with $\tau_* < 0.1$ Myr. Since the dynamical time scale of such regions and the growth time scale of the instability are $\sim 10^3$yr, which is $<<$ $\tau_{\rm growth}$, the GI scenario requires terrestrial planets to form well after the giants (Boss 2003). In disks with $f_g >> 1$, the efficiency of angular momentum transfer is strongly enhanced by the growth of unstable modes (Laughlin & Rozyczka 1996; Armitage & Hansen 1999) so that $\alpha > 10^{-2}$ and $\tau_{\rm mig} \sim 10^3$ yr. Giants' tidal interaction with gas in their co-orbital region of massive disks may also lead to rapid migration (Masset & Papaloizou 2003), though the magnitude of this effect remain uncertain (D'Angelo et al. 2005). Migrating giants would not capture each other into the observed mean-motion resonances (hereafter MMR) if their $\tau_{\rm mig}$ is shorter than their resonant libration time scale (Ida et al. 2000).

3. Emergence of close-in earths

With a series of simulations, we show that the embryos formed prior and interior to the giants are induced to migrate, collide, and evolve into close-in earths. We compute the evolution after the formation of the giants with a fourth-order time-symmetric Hermite scheme (Kokubo et al. 1998; Aarseth 2003) which includes the total force due to the star, planets, and disk (Mardling & Lin 2002; Nagasawa et al. 2003). The Σ_g distribution is assumed to

be that of the MMN with a gap (of width no less than the giants' R_h and epicycle amplitude). We adopt values of $\tau_{\rm mig}$, $\tau_{\rm depl}$, M_*, and M_p to be within the range of the observed values (Hartmann 1998; Marcy et al. 2005). We highlight some generic features with three representative models:

- a) a Jupiter-mass (M_J) giant formed at $a = 5.2AU$ with $e_p = 0$ (due to planet-disk tidal interaction (Papaloizou et al. 2001)) around a $1M_\odot$ star,
- b) two giants [with initial $(M_p, a, e_p) = (1.67M_J, 1.5{\rm AU}, 0.40)$ and ($3.1M_J$, 4.17AU, 0.24)] around a $1M_\odot$ star,
- c) a pair of giants [with initial $(0.56M_J, 3.3{\rm AU}, 0)$ and $(1.89M_J, 5.5{\rm AU}, 0)$] around a $0.32M_\odot$ star,

to represent systems around HD209458, μ Ara, and GJ 876 respectively.

In Model a), we adopt $f_g = 1$ and $f_d = 1.25$ which yield 27 embryos with initial $M_{\rm iso} = 0.1 - 0.26M_\oplus$ and separation $\Delta_{\rm fz} = 10R_h$ for $a = 0.49 - 2.10$ AU. (In all models, $M_{\rm iso} \sim M_{\rm core}$ and $\tau_{\rm growth}(M_{\rm core}) < \tau_{\rm dep}$ at $a > a_{\rm ice}$.) The orbits of embryos exterior to this range are rapidly destabilized by the giant whereas $M_{\rm iso}$ of the close-in embryos does not contribute significantly to the total mass ($M_{\rm tot} = 4.35M_\oplus$) of the population.

The giant is assumed to migrate over $\tau_{mig} \simeq 1.8$Myr ($\alpha = 10^{-4}$) and to stall at 0.1 AU. Embryos along the giant's migrating path are captured by its MMR's, migrate with it, and merge into four bodies with $M_p = 0.11$, 0.3, 1.09, & $1.92M_\oplus$ just inside its asymptotic 2:1 and 3:2 MMR's. Some captures also occur through the resonant interaction among the embryos. Since $e_p = 0$, this solitary giant's secular perturbation on the embryos is negligible. Due to the embryos' internal tidal dissipation (Novak et al. 2003) and relativistic precession (Mardling & Lin 2004), we anticipate a slight additional a_e decay and predict that short-period giants (*eg* HD 209458b) are accompanied by close-in earths (Figure 1).

In Model b), we choose $f_g = f_d = 4$, and $\tau_{\rm dep}(\sim 0.1{\rm Myr} < \tau_{mig})$ with $\alpha = 10^{-4}$. The fraction of T Tauri stars with such massive disks (Beckwith & Sargent 1996; Muzerolle et al. 2005) is comparable to that of nearby stars with known planets. The initial 26 embryos with $M_{\rm iso} = 0.23 - 1.25M_\oplus$ (a total of $14.7M_\oplus$) are separated by $\Delta_{\rm fz} = 12R_h$ at $a = 0.09 - 1.2$ AU. The secular interaction between the two planets (with M_j and a_j) introduces a precession in their longitudes of periapse ϖ_p (initially orthogonal) with two eigenfrequencies which are also modified by the disk's potential (Ward 1993; Nagasawa et al. 2003). Due to similar effects and the star's post-Newtonian gravity, the embryos (with a_e and mean motion n_e)

also precess with the frequency

$$\dot{\varpi}_e = n_e[\sum_{j=1,2} \frac{M_j}{4M_*} \alpha_j^2 b_{\frac{3}{2}}^{(1)}(\alpha_j) + 2\pi f_{\rm dep} Z(k) \frac{\Sigma_g a_e^2}{M_*} + 3(\frac{n_e a_e}{c})^2]. \tag{4}$$

Here $\alpha_j = a_e/a_j$, c is the speed of light, and the power index of Σ_g in MMN is $k = 3/2$, for which the constant $Z(k) = -0.54$. Secular resonance (hereafter SR) occurs at locations a_s where $\dot{\varpi}_e = \dot{\varpi}_p$. The resonant embryos' e_e are excited by the nearly aligned periapse ($\varpi_e - \varpi_p$) and damped by the gas drag which also leads to orbital decay (Nagasawa et al. 2005). All precession frequencies and a_s decrease with the disk depletion over $\tau_{\rm dep}$, leading to a sweeping SR. As their orbits cross, the embryos coagulate into two bodies with $(M_e, a)\sim$ $(7M_\oplus, 0.23\text{AU})$ and $(4M_\oplus, 0.052\text{AU})$ (Figure 2).

In Model c), we adopt $f_g = f_d = 1$, $\tau_{\rm dep} = 1$ Myr, and $\tau_{mig} = 1$ Myr ($\alpha = 10^{-3}$) for the outer planet. The initial 24 embryos (with $0.04M_\oplus < M_{\rm iso} < 1.49M_\oplus$ and a total $\sim 7.2M_\oplus$ separated by $\Delta_{\rm fz} = 12R_h$ between 0.07–0.72 AU) extend outside the snow line ($a_{\rm ice} = 0.28$ AU). With an external disk, the outer planet undergoes orbital decay, captures the inner planet onto its MMR, and they continue to migrate together. The resonant excitation of the outer planet's e_p is damped by the outer disk (Kley et al. 2004) over $\tau_{\rm pdamp} \sim 0.1\tau_{mig}$. The inner planet's damping rate is assumed to be reduced by the gas depletion in the gap.

Although the embryos' initial $a_e << a_p$, their e_e's are excited by the giants' perturbation and damped by their interaction with the disk. These effects lead to a_e decay (Nagasawa et al. 2005) on a time scale $\sim e_e^{-2}\tau_{\rm e,damp} > \tau_{\rm mig}$. As a_p approaches their a_e's, embryos are captured into the gas giants' MMR's. The resonant embryos are induced to 1) migrate, 2) capture other embryos, and 3) coagulate over $\tau_{\rm mig}$. After the giants are stalled at 0.2 and 0.12 AU, they continue to excite e_e and reduce a_e through their secular perturbation and resonance, similar to Model b). After 1.4 Myr, three embryos remain with $(M_e, a)\sim$ $(1.5M_\oplus, 0.072\text{AU})$, $(5M_\oplus, 0.054\text{AU})$, and $(0.7M_\oplus, 0.036\text{AU})$ (Figure 3). Since we anticipate the giants' SR to sweep inward, embryos' e_e-damping to weaken, migration to slow, and coalescence to occur, we continue the calculation with a reduced $\tau_{\rm dep}$ (0.1 Myr) and find two remaining embryos after 1.7 Myr with ($6.5M_\oplus$, 0.056AU) and ($0.7M_\oplus$, 0.037AU). The giants' secular perturbation on the embryos is suppressed by the relativistic precession which limits $e_e \sim 0.01$. The embryos undergo fractional orbital decay as they tidally interact with the host star during its life span (Mardling & Lin 2004).

Extensive model analysis will be presented elsewhere. In general, the embryos' migration driven by the giants' MMR and SR are robust (independently of f_g, $\tau_{\rm dep}$, α). However, the asymptotic values of M_e and a_e are determined by f_d, $\tau_{\rm e,damp}$, M_p, the asymptotic values of e_p and a_p (which regulate e_e and embryos' response).

4. The origin of the close-in earth around GJ 876

We choose Model c) to represent the initial disk structure around GJ 876. Both f_g and f_d in Model c) are high for disks around low-mass stars (Muzerolle et al. 2005). If $M_{\rm disk} \propto M_*$ (*i.e.* $f_d \propto M_*$), $M_{\rm iso} << M_\oplus$ and $\tau_{\rm growth} >> \tau_{\rm dep}$ such that giants would rarely form around low-mass stars (Ida & Lin 2005). The total mass of refractory material interior to $a_{\rm ice}$ is $\sim f_d M_\oplus$. If the newly discovered planet is mostly composed of refractory material ($\sim 1.5\%$ of all that in GJ 876), f_d would need to be > 8 with a corresponding $M_{\rm disk} > 0.02 (f_g/f_d)(a/1{\rm AU})^{1/2} M_*$ which is gravitational unstable at $a > 1 - 2AU$.

Model c) reproduces the observed properties of GJ 876. The total amount of solids (mostly volatile ice) within 1AU is $\sim 7 - 8 M_\oplus$ and the condition for giant formation ($\tau_{\rm growth}(M_{\rm core}) < \tau_{\rm dep}$ see §2) is satisfied at $\sim$ 3AU (where the disk is gravitationally stable). This model suggests that the close-in earth was formed outside the snow line, mostly of water. While the detectable atmospheric H_2O is photo-dissociated by the stellar UV flux (Leger et al. 2004) and hydrogen atoms escape, the atmospheric oxygen atoms are separated from the silicate core by a deep ocean. This process may lead to non-biogenic formation of O_2, confusing the uniqueness of its bio-marker (Des Marais et al. 2002).

5. Summary

The ubiquity of close-in earths is inferred from the SA hypothesis because their formation is promoted by: 1) the anticipated formation of embryos prior to the emergence of giants, 2) the driven migration of the embryos by the giants' MMR and SR, 3) the tidal interaction between the embryos and their nascent disks, and 4) the embryos' induced collisions along their migration path. These effects are especially important for stars with multiple intermediate-period resonant planets. In the GI scenario, embryos cannot form prior to the giants. The giants' orbits evolve too rapidly for them to capture other giants and embryos onto their MMR's. Their detection through frequent radial velocity (Narayan et al. 2005) and sub-milli magnitude transit observations of known short-period and resonant giants could be used to extrapolate the probability of finding terrestrial planets around solar-type stars (Ida & Lin 2004).

A general $\Sigma_{d,g}$ distributions (other than MMN) may lead to diverse $M_{\rm iso}$, $\tau_{\rm growth}$, and planetary configurations including earths with a_e exterior to the a_p of giants (Raymond et al. 2005). Provided $\Sigma_{d,g}$ does not increase rapidly with a, close-in earths are expected to be associated with short-period giants.

In Model c), $a_{\rm ice}$'s around M stars are much closer to those around G stars (in models

a and b). We infer from the SA scenario a prolific production of water-rich close-in earths around these low-mass stars. Although their day-side temperature may exceed 500K, the night-side of these close-in earths may be much cooler (Burkert et al. 2005) because their atmosphere is likely to be covered by opaque clouds. Direct searches for these conspicuous close-in earths may reveal that terrestrial planets are ubiquitous and lead to the detection of habitable environment among them. However, the possibility of a physical origin for O_2 requires a reassessment of the biological implications for its future detection.

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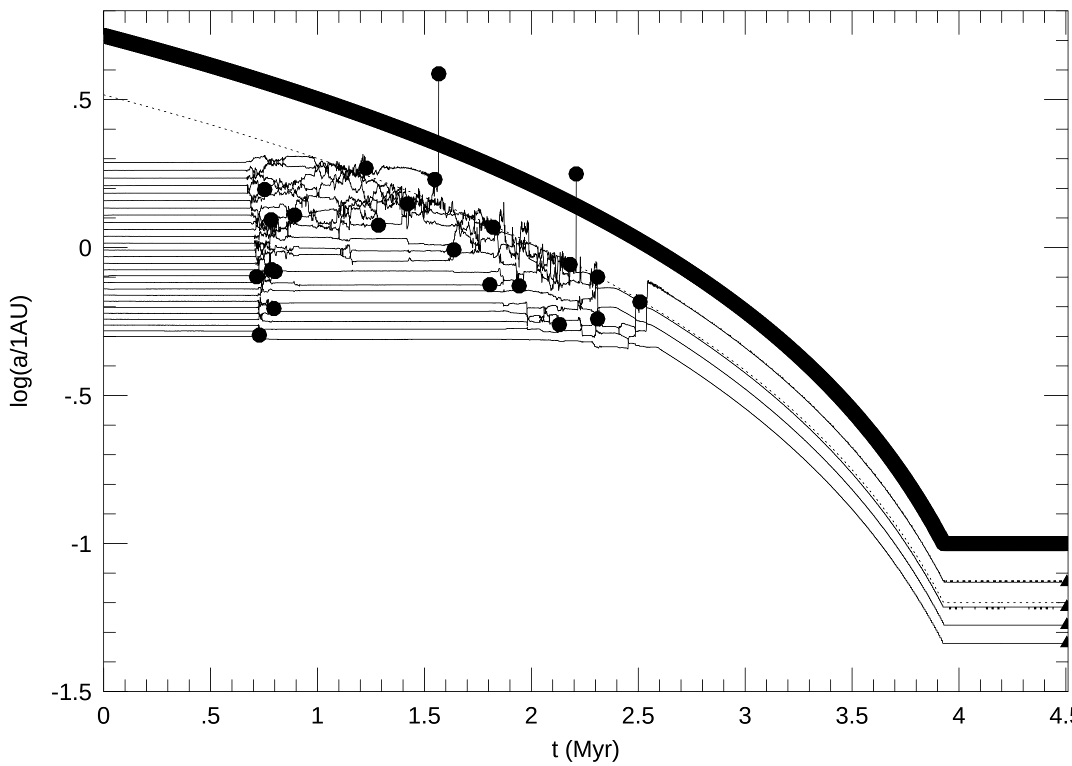

Fig. 1.— A solitary migrating giant captures residual embryos interior to the snow line onto its MMR. The time evolution of the semi major axes of the giant and embryos for Model a) is plotted with heavy and light lines. The dots and triangles represent collisions and final configurations, and the dotted line shows the location of 2:1 resonance with the planet. Under the combined influence of e_e-damping and the planetary resonant perturbation, the captured embryos migrate, collide, and grow.

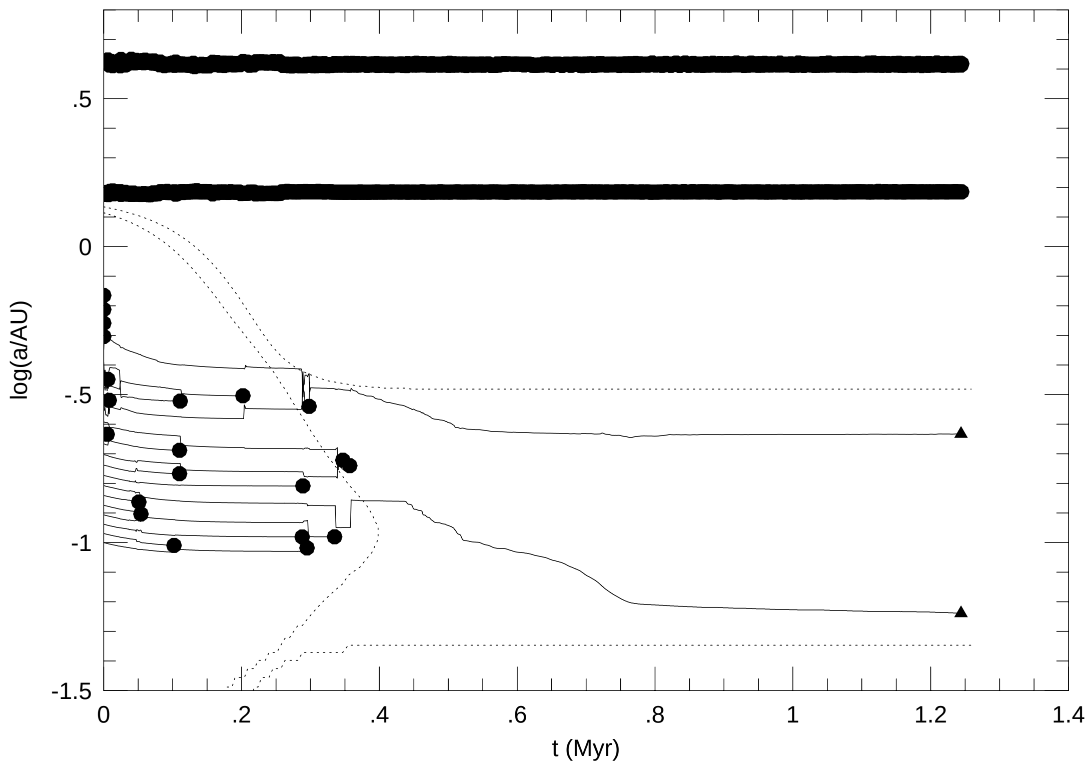

Fig. 2.— Embryos' migration and collisions induced by the giants' SR in Model b). As SR's (dotted lines) sweep inward (Ward 1981) from a_p and outward from the origin over $\tau_{\rm dep}$, the migrating embryos collide and grow in agreement with theory. They stall when the SR is significantly weakened or $\dot{\varpi}_e$ is dominated by the relativistic correction.

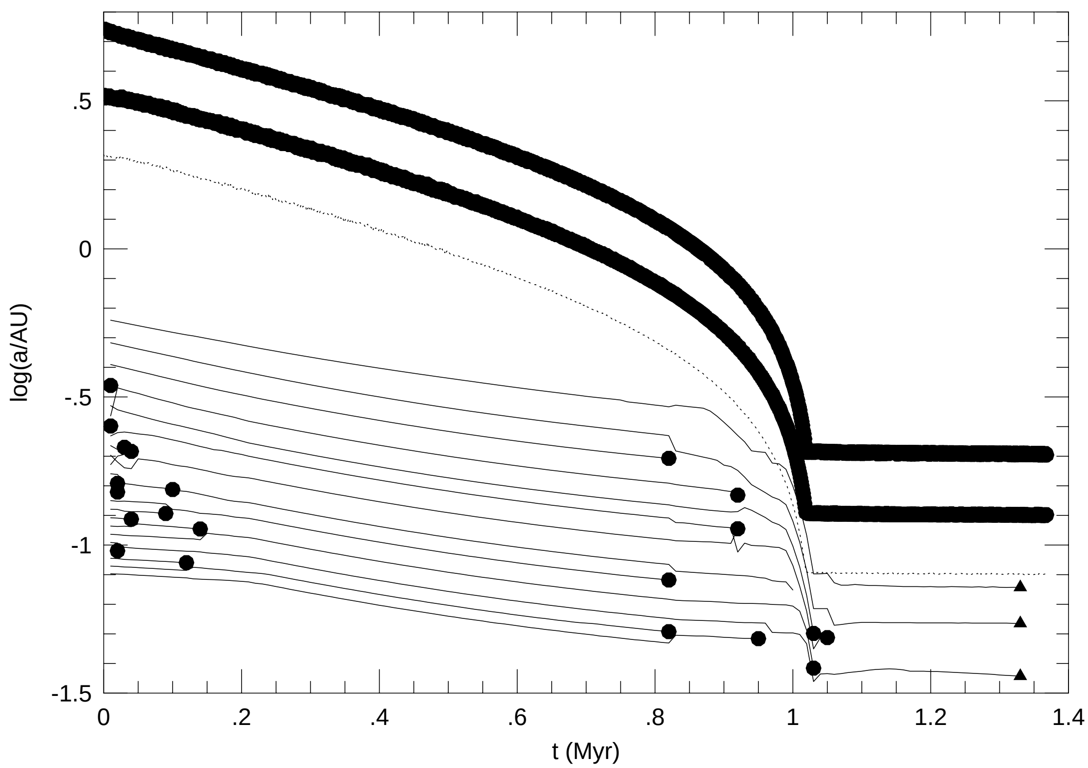

Fig. 3.— The embryos' resonant capture and forced evolution by migrating resonant planets in Model c). As their orbits cross, the embryos undergo cohesive collisions and grow. The dotted line shows the location of 2:1 resonance with the inner planet.